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FINAL REPORT

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THEORETICAL AND EXPERIMENTAL ACHIEVEMENTS IN THE FIELD OF INDUCED GAMMA EMISSION

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Abstract

A critical analysis is presented for all published to date experimental data concerning the induced gamma-emission (*IGE*) in processes $^{125m2}Te(\gamma, 2\gamma)^{125m1}Te$, $^{123m2}Te(\gamma, 2\gamma)^{123m1}Te$, and $^{119m2}Sn(\gamma, 2\gamma)^{119m1}Sn$. The co-operative model of the *IGE* phenomenon is deduced from quantum electrodynamics.

Experimental results

In 1984 we published[1] a results of experimental study regarding the *IGE* process:

$$^{125m_2}Te + h\nu(109.3keV) \xrightarrow{78K} {}^{125m_1}Te + 2h\nu(109.3keV) \quad (1)$$
$$\downarrow 1.48ns$$
$$^{125}Te + h\nu(35.5keV)$$

In Ref.[1] the experimental effect is taken as:

$$\varepsilon = \frac{\Delta\Phi}{\Phi}, \quad (2)$$

where $\Delta\Phi$ is the number of gamma-quanta emitted by stimulation at the $Be^{125m2}Te$ sample temperature T_{exp}=78*K*, and Φ is the number of gamma-quanta spontaneously emitted at sample temperature 300*K*. The value ε_{exp} = 1.2±0.6% had been obtained in Ref. [1]. In order to exclude the contribution in ε_{exp} from a temperature rise of sample density we had reproduced the *IGE* process (1) in Ref.[2]. In the latter work the experimental effect is taken as:

$$\varepsilon_{exp} = \frac{\Phi_{2\gamma}}{\Phi}, \quad (3)$$

where $\Phi_{2\gamma}$ is a number of coherent pairs $2h\nu$ (109.3 keV) originated in the process (1).

Finally, in Ref.[3] we had reproduced the *IGE* process (1) using both techniques (2) and (3) . for ε_{exp}. The resulting experimental data are presented in Table 1.

Taken together References [1-3] demonstrate with confidence a reality of the *IGE* process (1). Nevertheless, by the early 1990s there was some uncertainty as to the mechanism of the *IGE* process. Hence, we undertook the experimental study regarding the *IGE* process[3]:

$$^{123m_2}Te + h\nu(88.46keV) \xrightarrow{10K} {}^{123m_1}Te + 2h\nu(88.46keV) \quad (4)$$
$$\downarrow 0.19ns$$
$$^{123}Te + h\nu(159.0keV)$$

The obtained value of ε_{exp} for process (4) together with data for reaction (1) had demonstrated[3-5] that realized *IGE* process is a collective polynuclear superradiance rather than stimulated emission of Mössbauer radiation. The corresponding theoretical equation for the effect value can be written as[3-5]:

$$\varepsilon_{theor} = \frac{2\pi N_x f_m \beta \tau_{down}}{3\mu^3(1+\alpha)(\tau_{up} + \tau_{down})}, \quad (5)$$

where N_x is a number of inversion, f_m is the Mössbauer factor, β is a branching factor, μ is the linear losses coefficient, α is an internal conversion factor, τ_{up} is the upper level life time, and τ_{down} is the lower level life time. Eqn. (5) holds[5] only when the lattice temperature ($T_{exp.}$) is decreased to the value T_Λ wherein a de Broglie thermal wavelength for nucleus $^*X$ exceeds the gamma-quantum wavelength (Λ):

$$T_{exp} \le T_\Lambda = \frac{(\hbar / \Lambda)^2}{2km_x}. \quad (6)$$

Here $\hbar$ is the Planck constant, k is the Boltzmann constant, and m_x is a mass for the $^*X$ nucleus. The relationship N_x=[$^*X$] was true in conditions of our experiments [1-5]. One should recognize from the data of Table 1 that Eqn. (5) of co-operative model describes within the error limits all the experimental results obtained in Ref.[1-5].

In Table 1 we present also the results of experimental study of the process (4) in ref.[6] and process

$$^{119m_2}Sn + h\nu(65.66keV) \xrightarrow{15-78K} {}^{119m_1}Sn + 2h\nu(65.66keV) \quad (7)$$
$$\downarrow 17.75ns$$
$$^{119}Sn + h\nu(23.87keV)$$

in Refs.[6,7].

Table 1. Comparison of theoretically calculated by formula (5) and experimentally measured ratio $\varepsilon=\Delta\Phi_\gamma/\Phi_\gamma$, where $\Delta\Phi_\gamma$ is the number of gamma-quanta emitted by stimulation at matrix temperature T_{exp}, and Φ_γ is the number of gamma-quanta emitted spontaneously at matrix temperature 300*K*.

nuclide (*X)	$^{125m2}Te$		$^{123m2}Te$		$^{119m2}Sn$	
polycrystal	*BeTe*		Mg_3TeO_6	Mg_3TeO_6 + *MgO*	*SnO*	SnO_2
T_Λ / *K*	10		6.6	6.6	3.6	3.6
Debye temperature / *K*	390		350	375	154	160
[*X] / 10^{18} atoms·cm^{-3}	12±5	4.9±1.5	34±7	1.0±0.2	5±1	9±3
T_{exp} / *K*	78	10	10	78	15	78
Mössbauer factor f_m (T_{exp})	0.10±0.02	0.108	0.18±0.01	0.13	0.0214	0.01
μ_0^{-1} / cm	0.2062	0.2062	0.1639	0.33	0.0293	0.032
$(4\pi/3)[*X]\mu_0^{-3}$ / 10^{16} atoms	44±18	18±6	63±13	16±5	0.053±0.011	0.12
$\frac{10^{20} f_m \tau_d}{2(1+\alpha_{up})(\tau_{up}+\tau_d)}$	4.03	4.35	0.148	0.103	0.0126	0.0059
ε_{theor} / %	1.8±0.7	0.8±0.3	0.09±0.02	0.02±0.01	$7.8\cdot10^{-6}$	$7\cdot10^{-6}$
ε_{exp} / %	1.2±0.6	0.35±0.15	0.05±0.03	0.30±0.06	≤0.0012	0.02± ±0.01
reference for ε_{exp}	Skor, Dz[1], 1984	Skor, Dz[3], 1995	Skor, Dz[3], 1995	Bond, Dz[6], 1996	*ITEPh*[7], 1989	Bond, Dz[6] 1996

Co-operative effects in stimulated emission

If we use a long-lived isomer both as storage and lasing level, the stimulated emission cross section is very small because of the very weak coupling between the gamma-radiation and the nuclei. Nevertheless, if the nuclei are imbedded in a lattice, co-operative effects in the stimulated emission could enhance the amplification and thus the gain substantially.

Consider an incoming gamma-radiation with a resonant (or near-resonant) frequency. That radiation interacts with all the nuclei in the ensemble and can stimulate those nuclei which are in the excited state to emit a photon. The probability for such a process can be written as[8]:

$$P_{stim.em.}(\hat{k}\sigma,t) = \left|\left\langle n_{\hat{k}\sigma}+1, \Psi_F(\vec{r}_1,\vec{r}_2,\ldots,\vec{r}_n,\vec{r})\left|\vec{J}(\vec{r})\cdot\vec{A}_{\hat{k}\sigma}(\vec{r},t)\right|n_{\hat{k}\sigma}, \Psi_I(\vec{r}_1,\vec{r}_2,\ldots,\vec{r}_n,\vec{r})\right\rangle\right|^2, \quad (2\text{-}1)$$

where $\vec{A}_{\hat{k}\sigma}(\vec{r},t)$ is the field at point $\vec{r}$ associated to the stimulating radiation with momentum $\hat{k}$ and helicity σ. For an incoming plane wave the vector potential is[9]:

$$\vec{A}_{\hat{k}\sigma}(\vec{r},t) = \vec{A}^*_{\hat{k}\sigma}\, e^{-i(\vec{k}\vec{r}-\omega t)} + \vec{A}_{\hat{k}\sigma} e^{i(\vec{k}\vec{r}-\omega t)}, \quad (2\text{-}2)$$

in which $\vec{A}^*_{\hat{k}\sigma}$ and $\vec{A}_{\hat{k}\sigma}$ are respectively related to the photon creation operator $a^+_{\hat{k}\sigma}$ and the destruction operator $a_{\hat{k}\sigma}$. Since we consider only stimulated emission we can write:

$$\vec{A}_{\hat{k}\sigma}(\vec{r},t) = a^+_{\hat{k}\sigma}\,\tilde{A}_{\hat{k}\sigma}(\vec{r},t). \quad (2\text{-}3)$$

The total nuclear current operator $\vec{J}(\vec{r})$ can be written as a sum of currents $\vec{j}_l(\vec{r})$ each belonging to one single nucleus. The position vector $\vec{r}$ can for each nucleus be written as a function of the position of the nuclear mass center $\vec{r}_l$ and a charge distribution vector $\vec{\rho}_l$. Then:

$$\vec{J}(\vec{r}) = \sum_l \vec{j}_l(\vec{r}) = \sum_l \vec{j}_l(\vec{r}_l+\vec{\rho}_l). \quad (2\text{-}4)$$

The wave functions of the initial and final state are products of single nucleus wave functions:

$$\Psi_I(\vec{r}_1,\vec{r}_2,\ldots,\vec{r}_n,\vec{r}) = \prod_l \int_{|\Delta\vec{r}_l|} \varphi_l(\vec{r}_l+\vec{\xi}+\vec{\rho}_l) f(\vec{\xi}) d\vec{\xi} =$$

$$= \int_{|\Delta\vec{r}|} \prod_l \varphi_l(\vec{r}_l+\vec{\xi}+\vec{\rho}_l) f(\vec{\xi}) d\vec{\xi}, \quad (2\text{-}5)$$

$$\Psi_F(\vec{r}_1,\vec{r}_2,\ldots,\vec{r}_n,\vec{r}) = \int_{|\Delta\vec{r}|} \prod_j \Phi_j(\vec{r}_j+\vec{\xi}+\vec{\rho}_j) f(\vec{\xi}) d\vec{\xi}. \quad (2\text{-}6)$$

Here the $f(\vec{\xi})$ function presents a Heisenberg uncertainty for the spatial coordinate $\vec{r}$.

As we consider only stimulated emission, we can restrict the initial state to all nuclei which are in the exited state. The total transition amplitude is then reduced to a sum of single nucleus matrix elements. Then, for every l in the absence of any temperature gradient in a lattice following relationship is true as result of the Heisenberg uncertainty relation:

$$|\Delta\vec{r}_l| = |\Delta\vec{r}| = \sqrt{\frac{2\pi\hbar^2}{m_X kT_{lat}}}, \tag{2-7}$$

where $\hbar$ is the Planck constant, k is the Boltzman constant, m_X is a mass of radiating nucleus, T_{lat} is a lattice temperature. Now instead equation (28) of Ref.[8] we obtain following equation for total transition amplitude:

$$\chi_{tot}(\hat{k}\sigma,t) = \sum_l \int_{|\Delta\vec{r}|} \left\langle \Phi_l(\vec{r}_l+\vec{\xi}+\vec{\rho}_l)\middle|\vec{j}_l(\vec{r}_l+\vec{\rho}_l)\vec{A}_{\hat{k}\sigma}(\vec{r}_l+\vec{\rho}_l)\middle|\varphi_l(\vec{r}_l+\vec{\xi}+\vec{\rho}_l)\right\rangle f(\vec{\xi})d\vec{\xi}. \tag{2-8}$$

Under condition $f(\vec{\xi}) = \delta(\vec{\xi})$ our equations (2-5), (2-6), (2-8) coincides with equations (26), (27), (28) of Ref.[8]. Instead of equation (29) in Ref.[8] the total transition amplitude becomes equal:

$$\chi_{tot}(\hat{k}\sigma,t) = \int_{|\Delta\vec{r}|} \sum_l \left\langle \Phi(\vec{\rho}+\vec{\xi})\middle|\vec{j}(\vec{\rho})\vec{A}_{\hat{k}\sigma}(\vec{r}_l+\vec{\rho},t)T(-\vec{r}_l)\middle|\varphi(\vec{\rho}+\vec{\xi})\right\rangle f(\vec{\xi})d\vec{\xi} =$$

$$= \sum_l \left\langle \Phi(\vec{\rho})\middle|\vec{j}(\vec{\rho})\cdot\int_{|\Delta\vec{r}|}\vec{A}_{\hat{k}\sigma}(\vec{r}+\vec{\rho},t)T(-\vec{r}_l-\vec{\xi})f(\vec{\xi})d\vec{\xi}\middle|\varphi(\vec{\rho})\right\rangle, \tag{2-9}$$

where:

$$\int_{|\Delta\vec{r}|}\vec{A}_{\hat{k}\sigma}(\vec{r}_l+\vec{\rho},t)T(-\vec{r}_l-\vec{\xi})f(\vec{\xi})d\vec{\xi} = \vec{A}_{\hat{k}\sigma}(\rho,t)\int_{|\Delta\vec{r}|}e^{-2i\vec{k}(\vec{r}_l+\vec{\xi})}f(\vec{\xi})d\vec{\xi}. \tag{2-10}$$

The total transition probability for stimulated emission can thus be written as:

$$P_{stim.em.}(\hat{k}\sigma,T_{lat},t) = |\ldots|^2\sum_{j,l}\int_{|\Delta\vec{r}|}e^{-2i\vec{k}(\vec{r}_l-\vec{r}_j+\vec{\xi})}f(\vec{\xi})d\vec{\xi}, \tag{2-11}$$

where:

$$|\ldots|^2 = \left|\left\langle\Phi(\vec{\rho})\middle|\vec{J}(\vec{\rho})\cdot\vec{A}(\vec{\rho},t)\middle|\varphi(\vec{\rho})\right\rangle\right|^2 = \hbar\omega_{res}A_{21}\frac{f_m(T_{lat})\beta\hbar\Gamma_{up}\hbar\Gamma_{tot}}{4(1+\alpha)\left[(E_{21}-\hbar\omega)^2+\frac{1}{4}(\hbar\Gamma_{tot})\right]}\cdot \tag{2-12}$$

Here β is a branching factor, α is an interval conversion factor, f_m is the Mössbauer factor, Γ_{up} is a line width of the upper level, Γ_{tot} is the total line width, A_{21} is the Einstein coefficient, $\hbar\omega_{res}=E_{21}$ is the energy of electromagnetic transition.

Under condition $|\Delta\vec{r}| << |\vec{k}|^{-1}$ there are both situations outlined by equations (32)-(36) of Ref. [8]. However, under opposite condition $|\Delta\vec{r}| \geq |\vec{k}|^{-1}$ we get:

$$\sum_{j,l}\int_{|\Delta\vec{r}|}e^{-2i\vec{k}(\vec{r}_l-\vec{r}_j+\vec{\xi})}f(\vec{\xi})d\vec{\xi} = \kappa(T_{lat})\sum_{j,l}1 = (N')^2\kappa(T_{lat}), \tag{2-13}$$

where:

$$N = [N] l_x l_y l_z, \tag{2-14}$$

$$l_j = Min(L_j, \mu_j^{-1}), \tag{2-15}$$

$$\kappa(T_{lat}) = \begin{cases} 1, & if \quad T_{lat} \le T_\Lambda \\ (T_\Lambda / T_{lat})^{0.5}, & if \quad T_{lat} > T_\Lambda, \end{cases} \tag{2-16}$$

$$T_\Lambda = \frac{(\hbar / \Lambda_{21})^2}{2km_X}, \tag{2-17}$$

L_j is the sample length along j-axis, μ_j is the absorption coefficient along j-axis, and Eqn. (2-17) is the same as Eqn. (6). Now one might see that equations (2-11) - (2-17) under condition $|\Delta\vec{r}| \ge |\vec{k}|^{-1}$ coincides completely with basic equation (5).

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References

1. G.A.Skorobogatov, B.E.Dzevitskii. Izvestja Acad. Sci. USSR, ser. Phys. (Russ.), 48 (1984) 1934.

2. V.G.Alpatov, G.E.Bizina, A.V.Davydov, B.E.Dzevitskii, G.R.Kartashov, M.M.Korotkov, G.V.Kostina, A.A.Sadovskii, G.A.Skorobogatov. Izvestja Acad. Sci. USSR, ser. Phys. (Russ.), 50 (1986) 2013.

3. G.A.Skorobogatov, B.E.Dzevitskii. Lasers Physics, 5 (1995) 258.

4. G.A.Skorobogatov, B.E.Dzevitskii. Il Nuovo Cimento (D), 17 (1995) 609.

5. G.A.Skorobogatov, B.E.Dzevitskii. Hyperfine Interactions, (1996) in press.

6. S.I.Bondarevskii, B.E.Dzevitskii, V.V.Yerjomin. Proc. of the International Conference LASERS'96. (Dec. 2-6, 1996, Portland, USA).

7. V.G.Alpatov, A.A.Antipov, G.E.Bizina, S.K.Godovikov, A.V.Davydov, G.R.Kartashov, M.M.Korotkov, P.A.Polozov, B.I.Rogozev, A.A.Sadovskii, I.A.Suvorov, A.I.Cheltsov. Izvestja Acad. Sci. USSR, ser. Phys. (Russ.), 53 (1989) 2052.

8. G.Neyens, R.Coussement.Hyperfine Interactions, (1996) in press.

9. F.H.Read. In "Electromagnetic Radiation", Chichester - New York - Brisbane - Toronto: John Wiley and Sons, 1980.